

Lead tungstate calorimeter of the Jefferson Lab Eta Factory experiment

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Abstract. A new electromagnetic calorimeter (ECAL) consisting of 1596 lead tungstate PbWO_4 scintillating crystals has been fabricated and installed in the experimental Hall D at Jefferson Lab (JLab). The high-granularity, high-resolution calorimeter is required by the JLab Eta Factory experiment, whose main physics goal is to study rare decays of eta mesons. The ECAL replaced the inner part of the forward lead glass calorimeter of the GlueX detector. The ECAL is integrated into the trigger system of the GlueX detector using electronics modules designed at JLab. Signals from the detector will be digitized using twelve-bit flash analog-to-digital converters operated at a sampling rate of 250 MHz. The ECAL is currently at the commissioning stage and should be ready for the physics run in January 2025. We will give an overview of the JEF experiment, the design and construction of the ECAL, and the integration of the detector and its infrastructure into the Hall D experimental setup.

1 Introduction

The GlueX detector [1] in experimental Hall D at Jefferson Lab (JLab) was designed to perform experiments using a photon beam incident on various targets. The main goal of the JLab Eta Factory (JEF) experiment [2, 3] is to perform measurements of various $\eta^{(\prime)}$ decays with emphasis on rare neutral modes. The physics program includes searches for gauge bosons coupling the dark sector to the Standard Model sector, precision tests of low-energy QCD, determination of the quark mass ratio, and others. The experiment requires good reconstruction of photons in the forward direction, which can be achieved by using an electromagnetic calorimeter (ECAL) based on high-granularity high-resolution lead tungstate PbWO_4 scintillating crystals. The ECAL replaced the inner part of the GlueX forward lead glass calorimeter. Prior to the construction of the large-scale ECAL detector, we built a prototype, which was used to study performance of ECAL modules and light monitoring system, and to optimize the design of the front-end electronics for the JEF operating conditions. The prototype consisted of an array of 12×12 cm PbWO_4 modules and was successfully used in the PrimEx- η experiment in Hall D to reconstruct Compton scattering events. The performance of the prototype is presented in [4]. In this paper we will describe the design, fabrication, and installation of the ECAL on the forward GlueX calorimeter and also give an overview of the ECAL electronics and integration of the detector into the GlueX trigger system.

The construction of the ECAL started in 2022 and the detector will be fully commissioned in the early fall of the

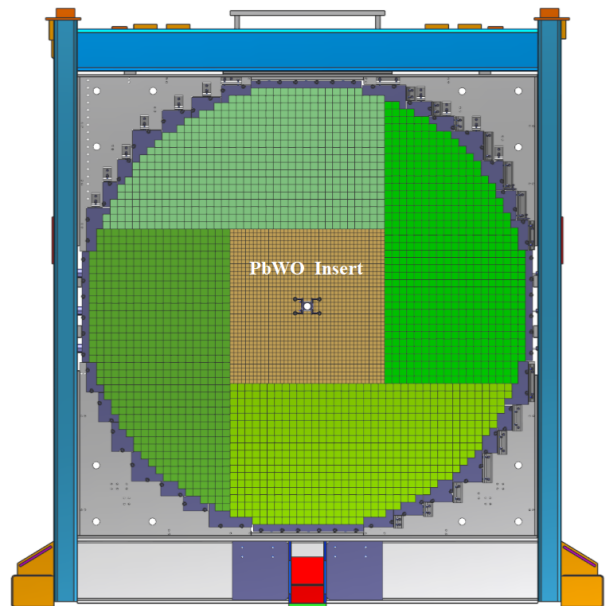


Figure 1. The frame of the GlueX forward calorimeter with the ECAL modules (brown rectangular area in the center) surrounded by lead glass modules (green). The photon beam passes through the hole in the middle of the ECAL.

2024. The total cost of the project is about 5 million dollars.

2 Calorimeter design

The ECAL consists of 1596 lead tungstate rectangular scintillating crystals. Each crystal has the following dimensions: $2.05 \text{ cm} \times 2.05 \text{ cm} \times 20 \text{ cm}$. The calorime-

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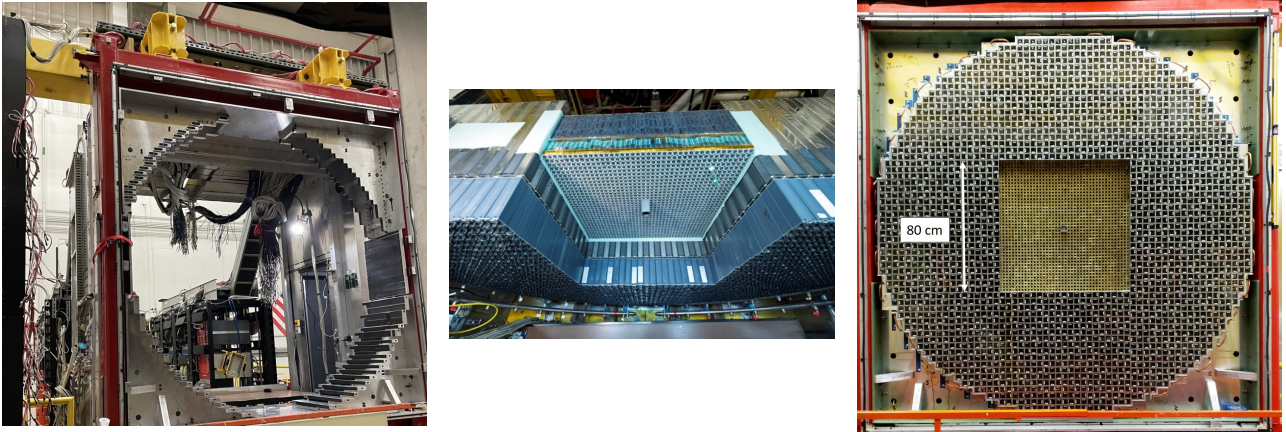


Figure 2. Installation of the ECAL modules on the GlueX forward calorimeter. The original calorimeter frame after removing all lead glass modules (left). Installation of the ECAL surrounded by the lead glass modules (middle). Installed calorimeter with the ECAL in the center of the detector (right).

ter modules are organized into an array of 40×40 modules with a hole of 2×2 modules in the middle for the beam. The PbWO_4 Type II crystals were purchased from two vendors: SICCAS (China) and CRYTUR (the Czech Republic). The properties of crystals used for the ECAL fabrication were studied in Ref. [5]. Main characteristics of the CRYTUR crystals, such as radiation resistance, light yield, and optical transmission, appeared to be somewhat more uniform compared to those from SICCAS. Consequently, we installed 918 available CRYTUR crystals in the region close to the beamline, where the detector will be exposed to higher radiation levels.

The ECAL replaced the inner part of the GlueX forward lead glass calorimeter, which originally consisted of 2800 modules with a block size of $4 \text{ cm} \times 4 \text{ cm} \times 45 \text{ cm}$. The schematic view of the hybrid PbWO_4 and lead glass calorimeter is presented in Fig. 1. In this plot, the ECAL is the rectangular brown area surrounded by the lead glass modules shown in green. The photon beam passes through the hole in the middle of the ECAL. The innermost ECAL layer around the beam pipe is shielded by a 6 cm thick tungsten absorber. All modules are placed inside the detector frame. The detector is positioned about 6 m downstream from the target and covers a polar angle between 0.3° and 11° for photons originating from the target. The smaller transverse size of the PbWO_4 crystals relative to the lead glass blocks will improve the separation of showers in the forward direction. The typical energy resolution of the lead glass calorimeter is $\sigma_E/E = 6.2\%/\sqrt{E} \oplus 4.7\%$ [1], which is more than a factor of two worse compared to the ECAL. The radiation resistance of lead tungstate crystals is superior to lead glass, which is important for the long-term operation of the calorimeter at high luminosity.

During the installation of the ECAL, the lead glass calorimeter had to be fully disassembled. Since the light output of the PbWO_4 crystals depends on temperature, the frame surrounding the detector modules was modified by installing cooling blocks with build-in pipes to circulate cooling liquid. The size and position of the cooling blocks

in the frame was chosen to accommodate the different size of the PbWO_4 and lead glass blocks. The entire detector was positioned inside a foam-insulated, light-tight box. During operation, the detector will be maintained at a temperature of approximately 17° C with expected stability better than 0.2° C . After installing the new detector frame, lead glass and ECAL modules were stacked together. The module installation was organized into several groups of layers. After installing each group of layers, the modules were squeezed by a movable cooling block from one side of the detector. A thermally conductive silicon pad (Saint-Gobain ThermalCool) with a compressed thickness of about $600 \mu\text{m}$ was applied as a compliance layer between the lead tungstate insert and lead glass modules. The main steps of the detector installation are presented in Fig. 2, with the fully installed calorimeter shown on the right plot.

3 Module design

The ECAL has a modular structure. An assembled calorimeter module and its main components are presented in Fig. 3. A lead tungstate crystal wrapped with a $65 \mu\text{m}$ thick reflective ESR foil and light-tight Tedlar is connected to a 3.5 cm long acrylic light guide using a 1.8 mm thick silicon rubber disk (cookie). The other end of the light guide is glued to a Hamamatsu 4125 photomultiplier tube (PMT) using Dymax 3094 UV curing glue. The PMT is surrounded by a $350 \mu\text{m}$ cylinder and $50 \mu\text{m}$ thick mu-metal foil and is positioned inside a soft iron housing. The cylinder is separated from the PMT housing using a thin Kapton film.

The PMT housing is required to reduce the fringe field of the solenoid magnet present in the calorimeter region, while the light guide extends the shielding above the face of the PMT photo cathode. The maximum magnetic field components directed along the PMT (longitudinal) and perpendicular to the PMT (transverse) are about 60 Gauss and 10 Gauss, respectively. The PMT magnetic shielding was studied using the TOSCA magnetic field simulation

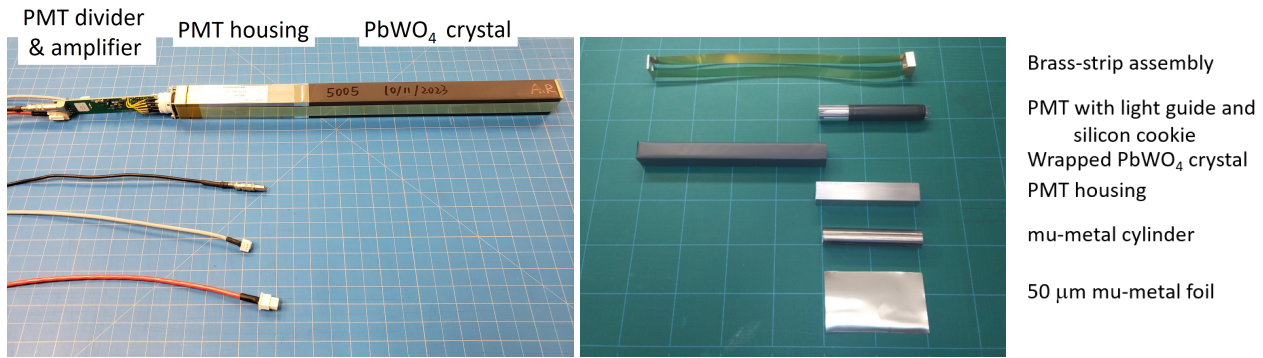


Figure 3. Assembled ECAL module with the attached PMT active base with signal, HV, and LV cables (left plot). Main components used for the module fabrication (right plot): the PbWO_4 crystal wrapped with the ESR reflective foil and Tedlar, PMT housing, brass strip assembly and mu-metal shielding.

program and verified with detector prototypes positioned inside magnetic field produced by Helmholtz coils. The performance of the PMT in the magnetic field was studied using an LED pulser.

The module components are held together using a brass-strip assembly, which consists of two $50\ \mu\text{m}$ thick brass strips soldered to two brass flanges. One flange is placed on the crystal face, and the other on the PMT housing. Four set screws in the PMT housing flange stretch the strips and hold the components together. A PMT with the light guide is pushed towards the silicon cookie by a G-10 retaining plate with four screws connected to the housing flange.

4 Electronics and trigger system

The distribution of high voltages (HV) to the PMT dynodes and the readout of electrical pulses are managed by the PMT active base designed at Jefferson Lab. The base incorporates a PMT divider and an amplifier positioned on the same printed circuit board (PCB). To improve gain stabilization at high rates, the original Hamamatsu divider design for this type of PMT was modified by adding two bipolar transistors to the last two dynodes. The amplifier, with a gain of about three, allows for a lower PMT operating voltage, thereby reducing the anode current, which also improves the rate capability and prolongs the PMT's life. This is particularly important for the ECAL modules positioned close to the beamline, which are exposed to the large rate of several hundred kilohertz at the readout threshold. The operational-based amplifier requires $\pm 5\ \text{V}$ power, which is supplied to the active bases by two WIENER MPOD modules. The typical high voltage applied to the PMT active base is about 1 kV. The high voltage for each PMT is provided by a 48-channel CAEN A7030N module, with thirty six modules positioned in three SY4527 mainframes. The active base with the attached signal, high voltage, and low-voltage cables is presented in the left plot of Fig. 4. Before installing on the detector, all fabricated ECAL modules and dividers were tested using an LED test setup. Installation of the active

bases on the ECAL PMTs is presented in the right plot of Fig. 4.

Signals from the PMT are digitized using a twelve-bit 16-channel flash ADC designed at JLab. The flash ADC operates at a sampling rate of 250 MHz and is equipped with Field-Programmable Gate Array (FPGA) chips, which allow programming the readout and trigger processing algorithms. One hundred flash ADCs are positioned in 7 VXS crates. The VXS (ANSI/VITA 41.0) crate extends the VME/VME64x architecture by implementing a high-speed bus used to transmit flash ADC data to the trigger module located in the middle of the crate. The digitized amplitudes (energies) in each flash ADC are stored in the FPGA-based pipeline for the VME readout and are summed over all 16 channels and sent to the VXS trigger processor module (VTP). The VTP processes amplitudes received from all flash ADCs in the crate and sends the resulting sum via a fiber optical link to the global trigger processor situated in the trigger crate, which makes the final trigger decision. The main physics trigger of the JEF experiment is based on the energy depositions in the forward and barrel calorimeters. The core module of the trigger system is the trigger supervisor (TS). The TS sends triggers to all readout crates to initiate the data readout, provides 250 MHz clock and synchronization signals. All information from the TS is distributed to GlueX crates through optical links. The GlueX trigger system has a fixed latency of about $3\ \mu\text{s}$, this is the time needed to make the trigger decision and distribute it to the readout modules. The typical trigger rate of the GlueX experiments is 60-70 kHz, with a data rate from the detector of about 1.3 Gbps.

5 Light monitoring system

The performance of each calorimeter module during data taking will be monitored using an LED-based Light Monitoring System (LMS). Light induced by multiple blue (and green) LEDs is mixed in an Integrating Sphere (Edmund Optics) with a diameter of 6 inches and distributed to each crystal using a plastic optical fiber with a core diameter of $500\ \mu\text{m}$. The surface-mount LEDs are soldered onto

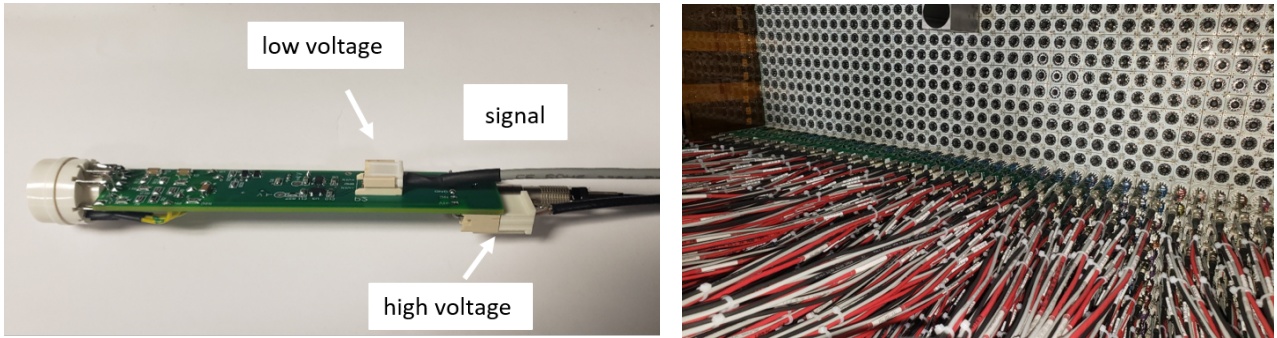


Figure 4. PMT active bases designed at Jefferson lab (left). Installation of the active bases on the ECAL PMTs (right). Each base is connected to signal, high voltage, and low voltage cables.

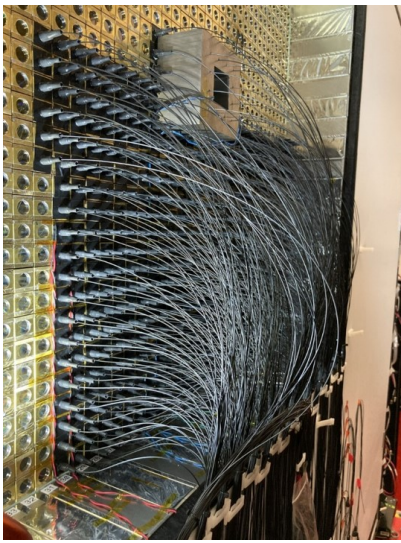


Figure 5. Installation of the LMS optical fibers. Optical fiber is glued to each PbWO_4 crystal through the hole in the flange on the face of the crystal.

a PCB, which is attached to the input optical port of the integrating sphere. All optical fibers are bundled and connected to the output port of the sphere. On the detector side, each fiber is attached to a small plastic cap, which is glued to the face of a PbWO_4 crystal using Dymax 3094 UV curing glue. After gluing, the face of each module is closed by light-tight tape to prevent optical crosstalk between modules. The installation of the optical fibers to ECAL modules is shown in Fig. 5. The stability of the LEDs is monitored using two reference PMTs that receive light from two sources: (1) a single fiber from LEDs and (2) a YAP:Ce scintillating crystal glued to the PMT activated by ^{241}Am α -source. The LEDs and reference PMTs are positioned inside the calorimeter temperature-stabilized room. The LED driver allows control over the LED pulse amplitudes and rates. The LMS is integrated into the GlueX trigger system and will be continuously operated with a typical rate of 10 Hz during data taking.

6 Summary

A new electromagnetic calorimeter based on 1596 PbWO_4 scintillating crystals has been fabricated and installed in experimental Hall D at Jefferson Lab. The ECAL will significantly improve the reconstruction of photons in the forward direction, thereby extending the physics potential of the GlueX detector. The ECAL is currently undergoing commissioning and will be ready for the first physics run in January 2025.

7 Acknowledgments

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